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THE SURPRISING BENEFIT OF CREATING STARS ON EARTH

by
R.W. CALLIS

FEBRUARY 2007

GENERAL ATOMICS

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ABSTRACT

In the 1950's, scientists at several locations around the world and in the U.S. began a quest to reproduce the energy of the sun and stars here on earth. Since the 1950's, scientists and engineers in the U.S. and around the world have worked hard to make an elusive dream come true: the creation of a source of energy that is unlimited, safe, environmentally benign, available to all nations and not dependent on climate or the whims of the weather.

Initial optimism about the ease of creating a controlled fusion reaction on earth soon gave way to the realization that this was an unparalleled technological and scientific challenge. While meeting the scientific and technological challenges of creating practical fusion energy has taken much longer than anticipated by the early fusion pioneers, the difficult challenges that have been met and extraordinary progress to date have brought with them unanticipated benefits in a wide variety of fields.

Although fusion has now evolved from a dream to a laboratory reality, there are still major challenges, which must be met before it can become a practical energy source. Addressing these challenges has and will continue to yield rich benefits for other fields of science and technology. Areas of understanding and technology that must be improved include:

- The physics of high temperature plasmas (which have very complex behavior),
- Cutting edge computational capabilities,
- Sophisticated methods for heating fusion plasmas to 100s of millions of degrees,
- Innovations in materials, magnets and control mechanisms,
- Creation of new diagnostics and sensors (how do you measure temperatures and pressures in something that's 100,000,000 degrees?),
- Complex engineering innovations (heat removal, remote maintenance, impurity removal, etc),
- Micromachining and manufacturing,
- Extremely accurate tracking and targeting.

The great progress that has been made to date in fusion research has been the result of a long series of important breakthroughs in both science and technology. Meeting these challenges has resulted in and will continue to result in important spin-offs and contributions to other areas of science and technology. This paper describes some of these spin-offs and contributions in the areas of superconductivity, medical/health, material processing, and waste remediation.

I. INTRODUCTION

A fusion reaction takes place when two small atoms combine to form a larger atom. When this occurs, substantial energy is released. This fundamental process of making larger atoms from combining smaller ones fuels the sun and the stars. Because of the strong electrostatic repulsion between two positively charged atomic nuclei, the ions have to approach each other at tremendous velocities so that the gap between the nuclei becomes small enough so that the strong nuclear forces can overcome the electrostatic repulsion.

Early in fusion research J.D. Lawson determined the conditions that would need to be met for fusion to become practical [1]. This criterion became know as the Lawson Criteria or the "Break Even Condition." The criteria states that, in order to have a fusion reaction produce as much fusion power as it takes to heat the plasma, the product of the ion density $n_i \left(m^{-3}\right)$, plasma temperature T_i (keV), and energy confinement time τ_E (s) must exceed the value of 10^{21} keV s/m^{-3} for a 50-50 mixture of deuterium–tritium fuel. There are three confinement scenarios which can produce these conditions: gravitational, magnetic, and inertial.

A. Gravitational Confinement

Gravity is one force that can hold a plasma together long enough so that the Lawson Criteria is satisfied. However the mass required to produce the gravity forces needed are only found in stars. Thus this is not an option for producing sustained fusion on earth.

B. Magnetic Confinement

Since plasmas have an electric charge, they can be bent, compressed, confined and/or otherwise held by magnetic fields. In fact the first two decades of fusion research was wholly devoted to magnetic confinement [2], exploring open ended devices as well as devices that close on themselves producing toroids. All efforts proved elusive with energy confinement being poor and the plasmas plagued with stability problems. Then in 1968 results from the Russians I. Tamm and A. Sakharov using a new type of magnetic confinement device called a tokamak (acronym from Russian for Toroidal Chamber in Magnetic Coils) caused a major stir. Their experiment ran at temperatures ten times higher (10 million degrees centigrade) than anywhere else in the world with excellent confinement results. The tokamak is characterized by toroidal symmetry with a helical magnetic field produced by current driven within the plasma as shown in Fig. 1.

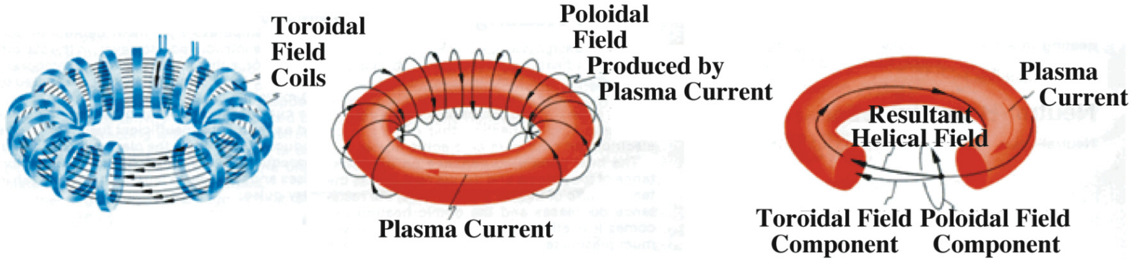

Fig. 1. The helical stabilizing fields within a tokamak are created by the vector summation of the toroidal fields produced by the exterior coil set, and the poloidal fields produced by current driven within the plasma.

Since the invention of the tokamak, the progress towards reaching the Lawson Criteria has been steady, with the anticipation that the next generation tokamak, ITER, will produce over 500 MW of fusion power. The progress is shown graphically in Fig. 2 [3].

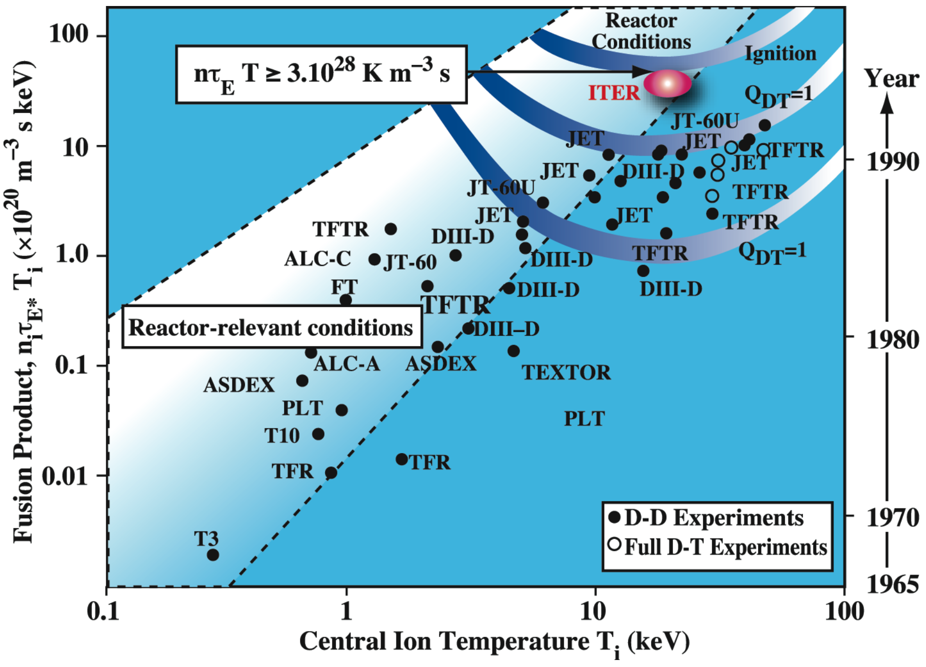

Fig. 2. This graphic shows the fusion triple product achieved on different magnetic fusion facilities [3]. Notice that the unit on the temperature scale, one keV, is equivalent to 11.6 millions of degrees. The graph shows clearly that new facilities performed better than previous ones.

The technology that was developed to support this impressive gain in fusion performance has spawned many spin-offs, some of which will be described later in this paper.

C. Inertial Confinement

Inertial Confinement Fusion (ICF) is a process where a capsule of fusion fuel is compressed and heated in such a short time period that the fuel ions, by their inertia, cannot escape the combustion cloud without experiencing multiple collisions eventually ending in a fusion reaction [4]. To compress and heat the capsule, lasers, ion beams, or x-ray radiation are used. The subsequent vaporization of the outer layer of the capsule sends shock waves to the core, compressing and heating the core to fusion reaction conditions. The energy released by this reaction additionally heats the remaining fuel producing more fusion reactions. If done correctly a condition known as “ignition” can be created, where the released fusion energy is large enough to support the combustion of the remaining fusion fuel without additional heat being applied. A diagram illustrating the inertial fusion sequence is shown in Fig. 3.

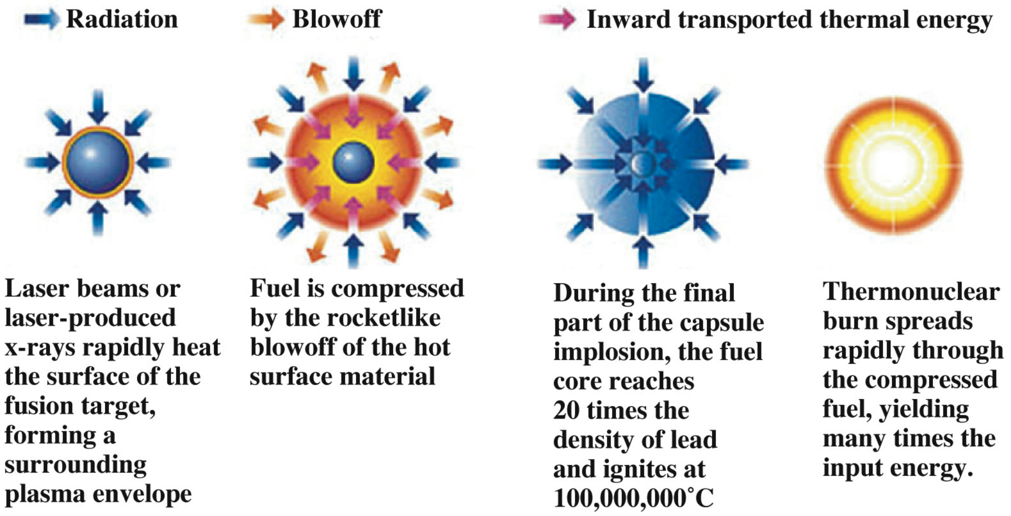

Fig. 3. The four steps of the inertial fusion process.

In the early 1970s, high power lasers became available and ICF research started in earnest. Development of ever more powerful lasers made rapid progress, with the anticipation that the “ignition” condition will be achieved with the National Ignition Facility (NIF) being built at the Lawrence Livermore National Laboratory (LLNL), with first operation anticipated in 2010. Unlike magnetic fusion devices, which basically have to be built at reactor level scales to achieve fusion conditions, ICF devices can demonstrate ignition conditions in single shot systems, while for Inertial Fusion Energy (IFE) systems with high rep rates (~10 Hz), and high laser efficiencies need extensive development. The progress of ICF and IFE is shown in Fig. 4.

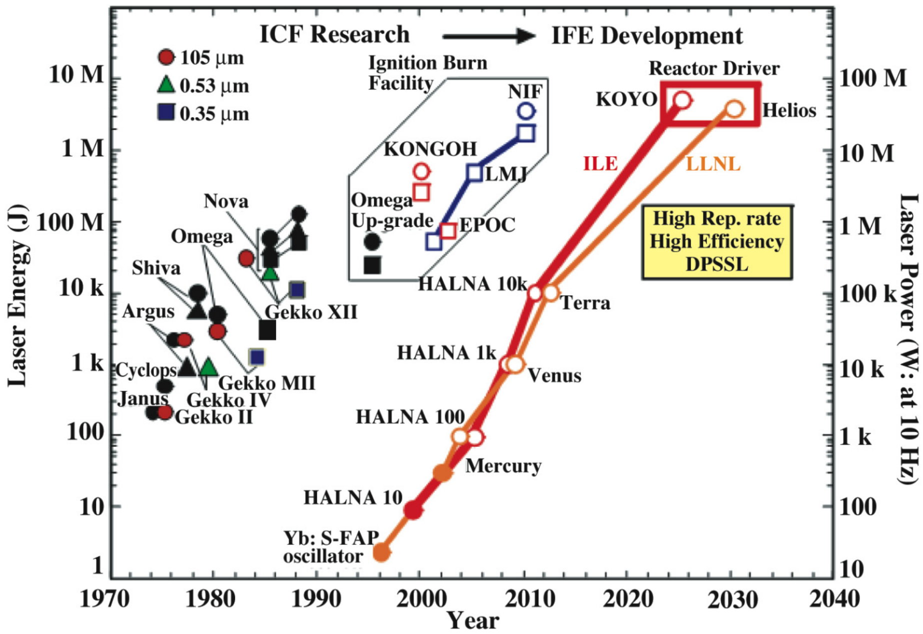

Fig. 4. Graph showing the development of ICF lasers since 1970. Lasers capable of "ignition" are shown in a box at the center of the graph. The lines shown on the right show development of repetition lasers needed to produce an IFE reactor by 2035. To date only the first two devices have been built. (Graph courtesy of S. Nakai)

II. FUSION RESEARCH AND INNOVATIONS IN MEDICINE AND HEALTH

Fusion scientists working with experts in the medical and health fields have allowed doctors to visualize objects within the human body without invasive surgery; to perform corrective surgery with less trauma and quicker recovery; to reduce the quantity of food lost to spoilage and contamination; and a new way of excavating cavities in teeth without drilling.

The Ultra-Short Pulse Laser developed in the fusion program can be used as a surgical tool to create high precision cuts without damaging surrounding tissue, or for tissue welding [5]. Lasers are used because they provide the ability to accurately control the volume of tissue that is exposed to the activating energy. Figure 5 shows laser welding of an artery during surgery.

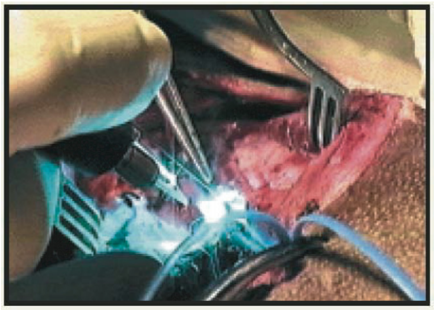

Fig. 5. Laser welding of an artery.

Researchers at LLNL have developed unique technologies to aid in the disruption of thrombus occlusions. This minimally invasive technique, Endovascular Photo-Acoustic Recanalization (EPAR), involves guiding a catheter to the site of the occlusion and introducing an optical fiber delivery system into the catheter. Laser light is coupled into the optical fiber and delivered to the occlusion, causing mechanical disruption of the occlusion and re-establishing blood flow to the brain [6]. Figure 6 shows how the shock wave emanates from the end of the fiber.

An x-ray catheter system to address a key element of heart disease treatment has been developed out of research in the ICF program [7]. Following balloon angioplasty to reopen occluded cardiac arteries, scar tissue often forms in the artery during the natural healing process, blocking blood flow. Known as restenosis, this clogging requires repeated surgery. Research has shown that treatment of the arterial wall with ionizing radiation immediately after angioplasty can prevent restenosis. The x-ray catheter is a safe, cost-effective means of delivering this ionizing radiation in the form of x-rays. Figure 7 shows a picture of an x-ray catheter.

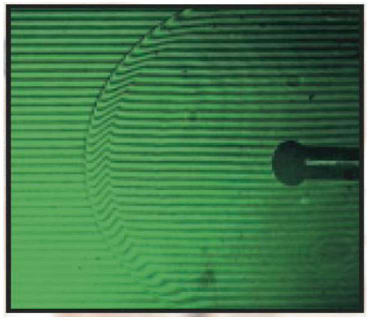

Fig. 6. Stress wave and vapor bubble created by laser energy deposited through an optical fiber.

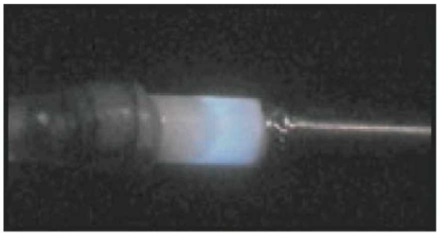

Fig. 7. X-ray catheter developed by LLNL.

Pulsed Electric Field (PEF) technology developed for fusion heating systems has been applied to food processing to destroy microorganisms and harmful enzymes. PEF processing uses a high-energy pulsed electric field to inactivate microorganisms and enzymes that cause spoilage in liquid foods. In a PEF processing system, juices and similar products are “pulsed” with a high voltage electric field as they pass through processing assemblies. With PEF processing, food is not heated so its fresh qualities are preserved. In contrast, thermal processing (e.g. pasteurization) can have a deleterious effect on a food’s taste, color, anti-oxidant content, and consistency. No chemical or radiation treatment is involved in PEF. The world's first commercial scale pulsed electric field (PEF) processing system, based upon Diversified Technology Inc.'s PowerMod™ electronics [8], is in operation at Ohio State University's Department of Food Science and Technology. The system is shown in Fig. 8.

Magnetic fusion research pioneered the development of large, precise, and economical superconducting magnets. Thus when Magnetic Resonance Imaging (MRI) started to become a standard tool as a painless procedure that can see through bone and clearly outline soft tissues, producing images that are extremely precise without exposing patients to radiation or radioactive solutions, fusion magnet engineers applied their knowledge to produce bigger and more economical MRI magnets. In 1984 General Atomics and Toshiba formed a joint venture to produce MRI magnets and now Toshiba Medical Systems is a world leader in delivering Open MRI Systems to the medical field. The joint venture has produce over 750 OPART MRI systems shown in Fig. 9.

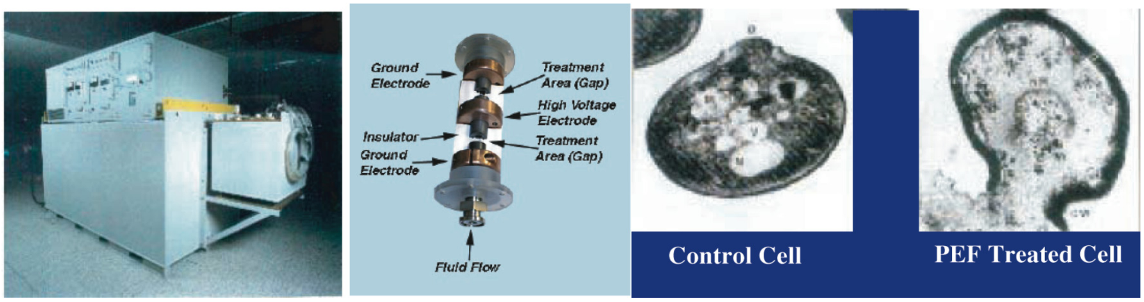

Fig. 8. As food moves through the tubes of the processing assemblies, a rapidly pulsed 65,000 volt (±65 kV) positive/negative electric field is applied. The field causes the cell membranes of microorganisms in the food to rupture, killing the cells and rendering them harmless.

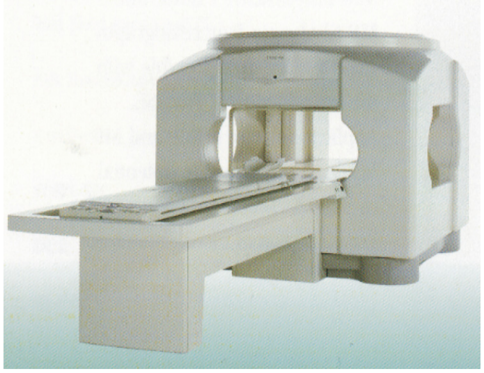

Fig. 9. OPART MRI System developed as a joint venture between Toshiba and General Atomics.

III. MATERIAL PROCESSING

The ever increasing challenge to the material science world to produce surfaces and material with greater endurance, harder surfaces, have less friction, less wear and more resistance to corrosion is being strongly supported by the use of fusion technologies.

Ultra high frequency microwave sources developed for the magnetic fusion program are being applied to a wide variety of material processing activities. Direct volumetric heating drastically speeds processing times and increases process efficiency. Some processes such as ceramic sintering occur more rapidly and at lower temperatures, resulting in improved product properties compared with conventional heating methods [9]. Microwave processing has numerous potential applications, including wood processing (drying, cracking, treating), grain or agricultural processing (drying or insect decontamination), chemical processing (dry or liquid), flash pyrolosis, and others. Presently there are three companies that commercially sell microwave sintering systems using gyrotrons developed for heating fusion plasmas. These are Communications & Power Industries (CPI), Fuji Denpa, and Gycom. Figure 10 shows the material sintering systems made by CPI, Gycom and Fuji Denpa.

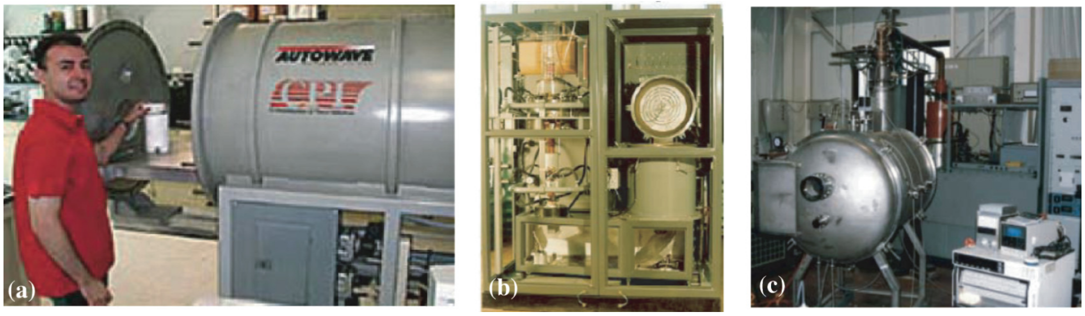

Fig. 10. (a) The CPI AutoWave System can be fitted with a 10 kW, 28 GHz gyrotron, (b) Gycom System 15 kW, 30 GHz, (c) Fuji Denpa sintering system 10 kW, 28 GHz.

It had been a long time desire of material scientists to develop synthetic diamond films for windows, because of diamond's superior optical, mechanical and thermal properties. In the 1990s this became a reality by the development of synthetic diamond using a Chemical Vapor Deposition (CVD) process, which uses a carbon rich microwave generated plasma and laying down of the carbon one monolayer at a time. This process is very time-consuming, with a 120 mm diameter, 2 mm thick window taking 3 months to produce. Scientists at the Russian Institute of Applied Physics have demonstrated that this process can be accelerated if a 30 GHz gyrotron developed for fusion research by Gycom is used to produce the carbon seed plasma [10]. This process called Enhanced CVD or ECVD reduces the production time by over a factor of three. Figure 11 shows a 75 mm diameter 1.35 mm thick window produced by the ECVD process.

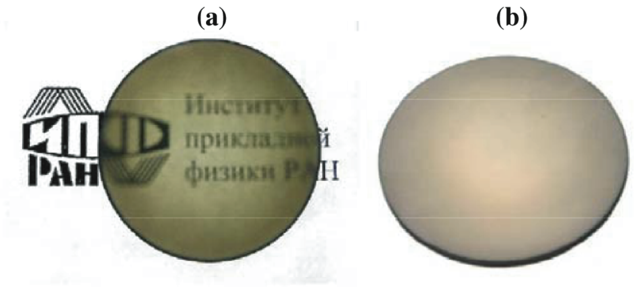

Fig. 11. IAP diamond disk of 75 mm in diameter: (a) as grown (1.6 mm thickness at the center), (b) the disc after polishing -1.35 mm thickness.

The pursuit of better and cheaper crystals for laser fusion has yielded a “rapid-growth” method to produce the world's largest single crystal optical elements [11]. The pyramid-shaped KDP (potassium di-hydrogen phosphate) crystal measures 52 centimeters (over 20 in.) across at the base and weighs nearly 500 pounds (Fig. 12.). The faster processing allows scientists to grow the record crystal in six weeks; previous methods would have required a growing period of 12-24 months to achieve the same result. By understanding and then controlling the crystallization process at the molecular level, complex microstructures can be synthesized that will affect many disciplines and technologies, ranging from life-saving pharmaceuticals (such as crystallized proteins, among them human insulin) to new optical material.

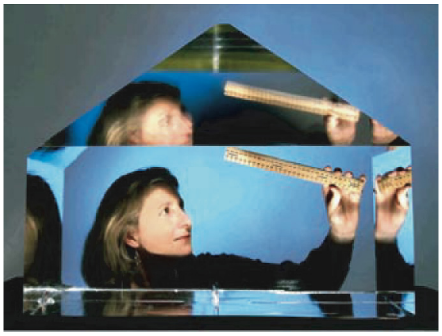

Fig. 12. Potassium Di-hydrogen Phosphate (KDP) crystal created by the rapid growth method.

Worldwide interest has increased in femtosecond lasers, developed for the inertial fusion program, due to their ability to perform high quality micro-machining in various materials. The Commercial Laser Group of General Atomics has responded to this interest and developed a dual-pulse technology (SuperPulse) solid state laser [12], which enables users to achieve enhanced material ablation, negligible recast material, and minimal heat affected zones in the drilling or cutting of materials, without the cost and complexity of standard femtosecond laser systems. Figure 13 shows a picture of a laser drilled hole 100 microns in diameter through 1 mm thick tool steel; note the cleanliness of the hole entrance and exit. The SuperPulse® lasers have produced 30 μm holes in diesel fuel injectors. Previous hole sizes obtained were 100 μm, but with new drilling techniques and higher quality beams, $30\,\mu m$ holes are now produced routinely in 1 mm thick steel plates and $50\,\mu m$ in 2 mm thick steel. Diesel engine manufacturers are required to reduce emissions by 2010 to the new standards as outlined in the Diesel Emissions Reduction Act of 2005. The smaller injector nozzle holes will allow engine manufacturers to meet these standards.

Fig. 13. Laser drilled hole in tool steel using a General Atomics SuperPulse® solid state laser.

Plasma-Source-Ion-Implantation (PSII) is a plasma based process for surface enhancement, which uses an ionized gas surrounding a target and high voltage, high current pulses to attract the ions into the target from all directions [13]. This process is equivalent to conventional ion beam implantation, but lends itself to more efficient batch processing. Diversified Technologies Inc. (DTI) has adapted high-voltage pulse power equipment used for fusion plasma heating research to coat parts with low friction diamond-like-carbon films, using the PSII method [14]. This process is very attractive to the automobile, aircraft, and machine tool manufacturers, who have long sought ways to enhance the surfaces of lightweight alloy parts to improve, wear lifetimes. Figure 14 shows a demonstration performed at Los Alamos where 1000 aluminum piston surrogates were coated with a long-life Diamond Like Carbon (DLC) coating using the DTI solid state modulator.

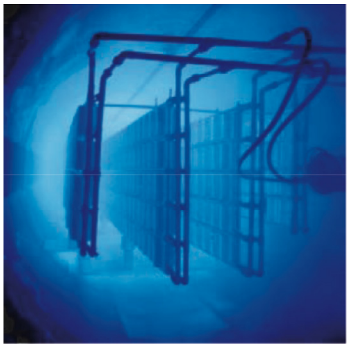

Fig. 14. Image of a target assembly of 1000 piston surrogates in a background Argon Plasma.

IV. IMPROVING THE ENVIRONMENT

Increasingly large volumes of toxic waste (created by manufacturing and by production and consumption of raw materials) require innovations in treatment to stabilize and reduce its volume needed for disposal. Plasmas, microwave and cryogenic technologies developed and associated with fusion development are helping make more efficient use of natural resources.

Fusion research at MIT on microwave-heated plasmas has produced an efficient electrodeless atmospheric plasma torch [15] (Fig. 15). This provides an environmentally superior treatment for waste remediation by providing controlled, high-temperature non-combustion processing free of hazardous emissions. (The process of plasma remediation of in-situ materials could provide a rapid, efficient, reliable and simple technique to selectively melt, vitrify or remediate contaminated soils, or objects at any depth underground.) It appears to overcome most of the limitations of thermal vitrification techniques using fossil fuels and electric heat sources.

Fig. 15. Microwave powered electrodeless plasma torch developed by MIT.

Scientists at Oak Ridge National Laboratory have developed an applicator that uses the high frequency gyrotrons developed for the electron heating of fusion plasma to ablate the surface of contaminated concrete (Fig. 16). The microwaves penetrate only a few millimeters into the concrete and heat the absorbed water to the boiling point, the flash boiling of the water literally pops off the top layer of concrete producing little to no dust [16]. A vacuum system incorporated into the applicator directs the contaminated debris into drums for disposal.

The ultra-high speed injection of cryogenically frozen pellets of fuel into high temperature plasmas is a key technology developed for fueling a fusion reactor. The Oak Ridge National Laboratory has fostered this technique for cleaning contaminated surfaces [17], using frozen carbon dioxide pellets shot at high speeds, as shown in Fig. 17. The effect is similar to sand blasting. The high-speed frozen pellets are an effective cleaning agent and leave no residue (other than the removed contamination itself) when they warm up and evaporate. A major attraction of this technology is its potential to minimize the generation of hazardous, radioactive and mixed wastes in the clean-up of nuclear facilities.

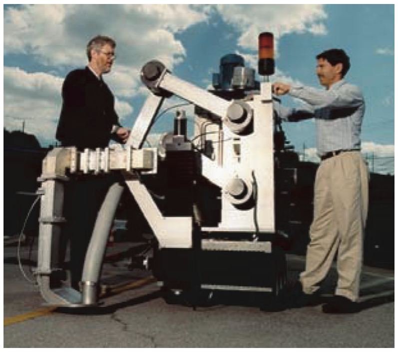

Fig. 16. Concrete surface ablator developed by ORNL using a 56 GHz fusion gyrotron.

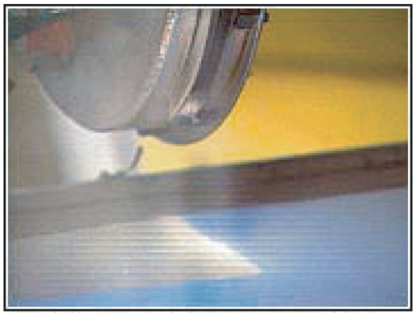

Fig. 17. The Cryogenic Blaster strips metal a lot like sandblaster except it is not as messy.

The understanding of basic plasma behavior has lead MIT engineers and colleagues to perfect a microplasmatron fuel converter (plasmatron) device that could turn foodstuff and various “biocrude” oils into fuel that could reduce the nation's dependence on foreign oil and decrease emissions of the greenhouse gas carbon dioxide [18]. The plasmatron could also significantly reduce the amount of smog-producing pollutants generated by vehicles running on traditional fuels. Essentially the device, which is about the size of a large soup can, works as an onboard “oil refinery.” It converts a wide variety of fuels into high-quality hydrogen-rich gas. Adding only a small amount of such gas to the fossil fuel powering a car is known to make possible a significant decrease in emissions of pollutants like nitrogen oxides. The plasmatron uses an electrically conducting gas (a plasma) to accelerate reactions, which generate hydrogen rich gas. Figure 18 shows a picture of the plasmatron.

Fig. 18. MIT Plasmatron.

V. SUPERCONDUCTIVITY

The engineering and technical developments that have produced large, precise superconducting magnets for the fusion program has lead directly to several applications outside the fusion community.

Much of the recent innovation within NMR spectroscopy has been within the field of protein NMR, which has become a very important technique in structural biology. Dynamic Nuclear Polarization (DNP) is a magnetic resonance technique utilized to enhance the polarization of nuclei through irradiation of the electron spins with microwaves in the neighborhood of their Larmor frequency [19]. Theory denotes signal enhancements corresponding to a factor of ~660 for ^{1}H nuclei and ~2600 for ^{13}C nuclei. Signal enhancements up to forty have been measured in the ^{13}C spectra of glycerol/water/TEMPO. An important component of this system is a compact 460 GHz fundamental gyrotron oscillator operating in the TE_{061} mode. A 9.4 T magnet with a 6.4 cm diameter vertical bore produces the magnetic field. This improvement to NMR spectroscopy utilizes two fields of fusion technology research, namely high field superconducting development, and high frequency gyrotron. Figure 19 shows a 460 GHz. 9.4 T DNP NMR spectrometer in test at MIT.

Fig. 19. A DNP NMR Spectrometer using a 460 GHz gyrotron and a 9.4 T superconducting magnet.

Fusion research is leading to the development of low cost High Temperature Superconducting (HTSC) material, which has the promise to revolutionize the electrical utility industry by improving the efficiency of several aspects of power generation and transmission. HTSC applications are being developed for generators, motors, transmission lines, energy storage, and surge limiters [20]. For example every lightning strike, short circuit and power fluctuation is a potential catastrophe for power companies and their customers. These common events cause fault currents, which are sudden, momentary surges of excess energy or current that can damage and destroy expensive transmission and distribution equipment and cut off service throughout a utility's grid. Superconductors are natural fault current limiters because of their ability to change rapidly from a superconducting, zero impedance state to a normal high impedance state in a fault situation. In this way, an HTS current controller can detect a power surge and redirect it to an HTS coil that can safely absorb the surge without tripping the circuit breakers. This device limits the impact of a fault current, ensuring uninterrupted power supply to the grid's customers, and protecting utility equipment. Figure 20 shows a picture of the cryomagnetic subsystem of a current limiter rated at 15 kV, 45 kA, 40°K, which was the largest HTC coil when built by General Atomics in 1999.

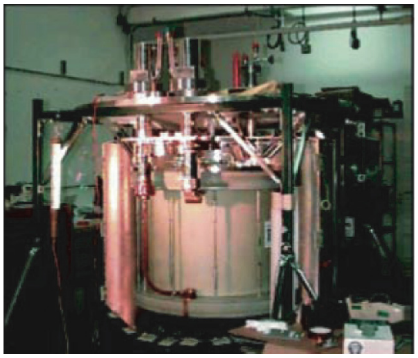

Fig. 20. A 15 kV, 45 kA, 40° K superconducting HTC current limiter built by General Atomics for the DOE.

VI. SUMMARY

It is apparent that the technology development that has been performed in the pursuit of fusion energy has lead to a significant number of spin-offs. The limited length of this paper does not allow for a complete coverage of this topic, contributions not covered are in the areas of space propulsion, semiconductor manufacturing, pulsed power conversion, and basic science. Besides these contributions to so many scientific and technological areas, another significant contribution is the cadre of scientists and engineers who have worked and trained in the pursuit of fusion energy and have taken their skills and knowledge out to the world scientific community.

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